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T2K latest results on neutrino-nucleus cross sections

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Abstract. Neutrino interaction cross section measurements are of high importance, in improving understanding for both oscillation measurements and nuclear modelling. The T2K experiment features a near detector complex with multiple detectors, providing multiple different nuclear targets at differing mean neutrino energies due to the off-axis configurations used. Along with constraining the flux for oscillation measurements, these near detectors provide the opportunity for a large programme of neutrino cross section measurements. Some recent such measurements are described in this proceeding.

1. Introduction

T2K (Tokai-to-Kamioka) [1] is a long-baseline accelerator neutrino experiment situated in Japan, designed to make precision measurements of neutrino oscillation parameters. This is achieved by studying the disappearance of muon neutrinos and appearance of electron neutrinos at the far detector Super-Kamiokande, in a beam of muon neutrinos created at the J-PARC accelerator complex in Tokai. The equivalent process for antineutrinos is also studied. Super-K is a 22.5 kt fiducial volume water Cherenkov detector, which additionally studies proton decay and neutrinos from a number of other sources [2].

To create the neutrino beam, protons accelerated up to 30 GeV impinge on a graphite target, creating multiple hadrons. Magnetic focussing horns are used to select out positive pions and kaons, which decay in flight to produce a beam of muon neutrinos – the polarity of magnetic horns is reversed to produce an antineutrino beam. The beam is directed 2.5° away from Super-K, which is situated 295 km away from the production point. This off-axis approach provides a narrow-band neutrino beam with a flux peaking at an energy of ∼0.6 GeV, allowing for more precise knowledge of the neutrino energy which cannot be directly reconstructed. It also optimises the ratio of the baseline to the energy $\frac{L}{E}$, so that the flux peak coincides with maximal oscillation probability.

At the range of energies covered by T2K, the majority of interactions proceed via charged current (CC) quasi-elastic (QE) scattering. However above the flux peak, neutrinos reach energies high enough to excite nuclear resonance (RES) states, producing additional mesons in the interaction. Between the CCQE and RES peaks, there is also a non-negligible component caused by interactions of a single neutrino with a number of bound nucleons. The most common form of this, involving two nucleons, is referred to as a two particle-two hole (2p2h) interaction. When a neutrino interaction occurs with an individual nucleon, the resultant particles must still escape the nuclear medium before being detected. In doing so, a multitude of final state interactions (FSI) can take place, altering the observed final state of the event. This is further complicated by the smearing effect introduced by imperfect reconstruction. Instead, cross section measurements are made in terms of the observed final state—henceforth known as the topology—which avoids relying too heavily on assumptions made by the underlying interaction generators. For example, the final state containing a single charged lepton and no mesons is known as CC0π—this will primarily be composed of CCQE interactions, with contributions from RES interactions where the outgoing mesons are not observed due to FSI, along with 2p2h interactions.

To make measurements of neutrino oscillation parameters, precise knowledge of the interaction cross section is required; systematic errors are currently dominated by cross section and flux uncertainties [3]. To help reduce this uncertainty, T2K has a dedicated cross section programme, with some recent results presented here.

2. The T2K Near Detector Complex

The T2K near detector complex is a suite of detectors, located 280 m downstream of the beam production point. The INGRID detector, centred on the beam axis, is a composite detector made of iron target plates and aligned plastic scintillator bars, which can sample the neutrino beam over an angular spectrum of 0 to 1.1° off-axis, and is used to constrain the flux of the beam.

At the same off-axis angle as Super-K is the ND280 detector, mounted inside the old 0.2 T UA1 magnet. The main target mass of ND280 is provided by two fine grained detectors (FGDs), which are composed of alternately aligned hydrocarbon (C_8H_8) scintillating bars. In addition, one of the two FGDs contains passive water layers, so that cross section measurements on H_2O can be made, which is the same target medium as in Super-K. The FGDs are layered between three time projection chambers (TPCs), which provide charge discrimination and particle momentum measurements from the curvature of tracks in the magnetic field. Energy-loss measurements in the TPCs are used to provide particle identification, which is a crucial tool for event selection in cross section analyses. The additional sub-detectors which are part of ND280 are the dedicated π^0 detector (PØD), electromagnetic calorimeters (ECals) for measuring electron and photon showers, and side muon range detectors (SMRDs). In 2022 an upgrade is planned for ND280, replacing the PØD with a greater resolution FGD, surrounded by TPCs and time of flight detectors oriented in such a way that they provide larger angular acceptance and lower tracking thresholds [4].

The most recent addition to the near detector complex is the WAGASCI detector, which at 1.5° off-axis sees a neutrino flux peaked at 0.86 GeV. WAGASCI has a mixed target mass: alternating planes and grids are formed from plastic scintillator, with the gaps in-between filled with water. This results in a ratio of water to hydrocarbon in the target mass of ∼80:20. WAGASCI was initially tested in a 'commissioning setup', which involved the WAGASCI module itself being sandwiched between an off-axis INGRID module (downstream) and the Proton Module (upstream). Originally used as part of the INGRID detector, the Proton Module is formed entirely of plastic scintillator bars, providing better resolution tracking compared to the standard INGRID modules. This allows for identification of both the muon and proton from CCQE events. Details of the full WAGASCI-BabyMIND setup, which has been in place since 2019 and includes a magnetised tracking detector, can be found in [5].

3. ν_μCC1π^+Np Transverse Kinematic Imbalance

A recent measurement performed by T2K is that of the ν_μCC1π^+ cross section with at least one proton in the final state topology (ν_μCC1π^+Np), which is made as a function of Transverse Kinematic Imbalance (TKI) variables. These variables, described in [6, 7], are formed from the transverse momentum components of the outgoing muon, pion, and highest momentum proton, and are sensitive to the initial nuclear state and FSI of outgoing hadrons.

The first such variable is δp_{TT}, the double transverse momentum imbalance. This is defined by forming a plane transverse to the incoming neutrino and outgoing muon directions, onto which the momenta of the pion and proton are projected:

$$\delta p_{\mathrm{TT}} = \frac{\vec{p}_{\nu} \times \vec{p}_{\mu}^{\mathrm{T}}}{\left| \vec{p}_{\nu} \times \vec{p}_{\mu}^{\mathrm{T}} \right|} \cdot \left(\vec{p}_{\pi}^{\mathrm{T}} + \vec{p}_{p}^{\mathrm{T}} \right), \tag{1}$$

where $\vec{p}_i$ is the momentum of the i^{th} particle, and $\vec{p}_i^{\mathrm{T}}$ is its component transverse to the neutrino direction. Assuming no nuclear effects, δp_{TT} should form a delta function centred on 0; deviation from this characterises the initial state of the bound nucleon and FSI of the outgoing pion and proton.

The second measured variable is the initial nucleon momentum, which is calculated as

$$p_N = \sqrt{\delta p_{\mathrm{T}}^2 + p_L^2}, \tag{2}$$

where

$$\delta p_{\mathrm{T}}^2 = \vec{p}_{\mu}^{\mathrm{T}} + \vec{p}_{\pi}^{\mathrm{T}} + \vec{p}_{p}^{\mathrm{T}}, \tag{3}$$

$$p_L = \frac{1}{2}\left(M_A + p_{\mu}^{\mathrm{L}} + p_{\pi}^{\mathrm{L}} + p_{p}^{\mathrm{L}} - E_{\mu} - E_{\pi} - E_{p} \right) - \frac{1}{2}\frac{\delta p_{\mathrm{T}}^2 + M_A^2}{M_A + p_{\mu}^{\mathrm{L}} + p_{\pi}^{\mathrm{L}} + p_{p}^{\mathrm{L}} - E_{\mu} - E_{\pi} - E_{p}}, \tag{4}$$

and the target nucleus is assumed to be at rest. This acts as a probe to the initial Fermi motion within the nucleus. The final variable is the transverse boosting angle,

$$\delta \alpha_{\mathrm{T}} = \arccos \frac{-\vec{p}_{\mu}^{\mathrm{T}} \cdot \delta \vec{p}^{\mathrm{T}}}{p_{\mu}^{\mathrm{T}} \delta p^{\mathrm{T}}}, \tag{5}$$

which describes how FSI alters the state of the outgoing hadrons; without FSI the $\delta\alpha_{\mathrm{T}}$ distribution should be flat, but FSI generally causes a deceleration of the outgoing hadrons, resulting in a higher plateau at $\delta\alpha_{\mathrm{T}} > 90°$.

The published measurement [8] is made with ND280 on the FGD1 hydrocarbon target, with the following phase space constraints applied to the outgoing particles: $250 < p_{\mu^-} < 7000$ MeV, $150 < p_{\pi^+} < 1200$ MeV, $450 < p_p < 1200$ MeV, $\theta_{\mu^-/\pi^+/p} < 70°$. Cross section extraction is performed using a binned likelihood minimisation to obtain the number of signal events, and four separate control samples describing events with multiple final state pions are used to constrain backgrounds. The resultant cross section measurements in Figure 1 show that some interesting model separation is observed. The expected broadening of the δp_{TT} and p_N distributions results in the more simplistic Fermi gas (RFG and LFG) nuclear ground state models being disfavoured by data. Due to tight phase space constraints on the selection, less sensitivity is observed in $\delta\alpha_{\mathrm{T}}$, but the higher angular acceptance from the ND280 upgrade should make this variable a crucial probe of FSI effects in future measurements.

4. Inclusive ν_eCC and $\bar{\nu}_e$CC at ND280

In measurements of the electron neutrino appearance probability, a large background comes from the intrinsic contamination of electron (anti)neutrinos in the muon (anti)neutrino beam, originating from kaon and muon decays. This contamination is expected to be a large source of uncertainty for future measurements of δ_{CP}. A recent measurement by T2K [9] reports the inclusive ν_eCC and $\bar{\nu}_e$CC cross sections, made on the FGD1 hydrocarbon target at ND280.

This measurement is made using three signal samples. The first contains events selected as having a single final state electron, from the neutrino mode (forward horn current (FHC)) data

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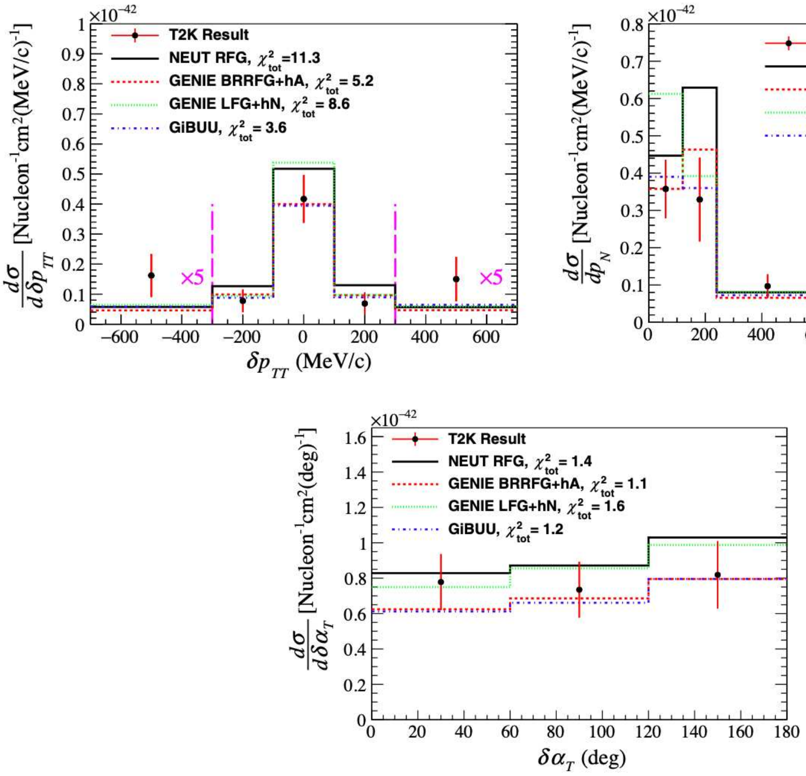

Figure 1: Measured ν_μCC1π^+Np cross sections as a function of $\delta p_{\rm TT}$, p_N and $\delta\alpha_{\rm T}$ compared with model predictions [8]. Tails of $\delta p_{\rm TT}$ and p_N are multiplied by 5 for clarity.

samples. The other two are selected from the antineutrino mode (reverse horn current (RHC)) data sets, where the first of these selects events with a single final state positron corresponding to a $\bar{\nu}_e$, and the second a single final state electron in order to categorise the non-negligible contamination of ν_e in the $\bar{\nu}_\mu$ beam. These signal samples suffer from a major background of photons from π^0 producing events, and thus a dedicated control sample for this is used.

Single differential cross section results for these signals are extracted as a function of the e$^\pm$

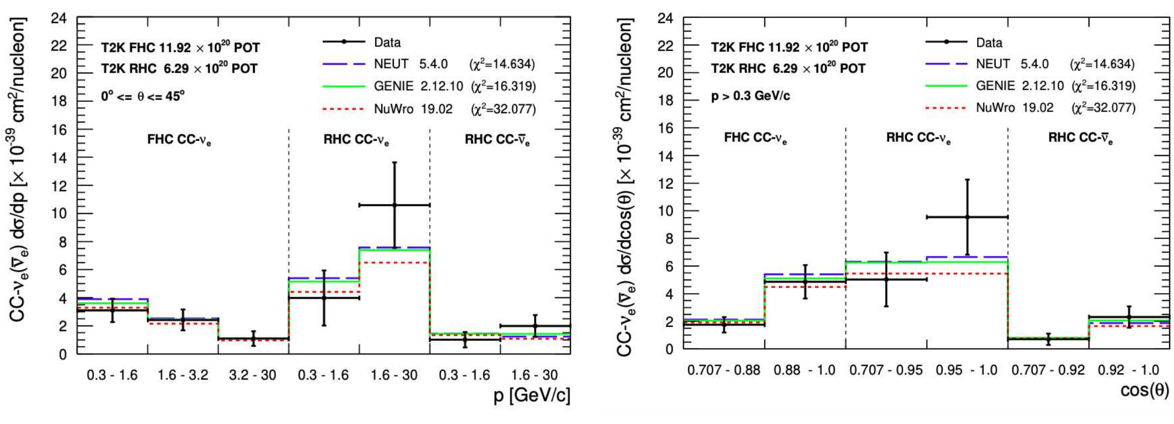

Figure 2: ν_e and $\bar{\nu}_e$ inclusive cross sections as a function of $e^\pm$ momentum (left) and angle to the neutrino direction (right), with comparisons to generators [9].

momentum and angle to the neutrino direction, in the limited phase space of $p_e > 0.3$ GeV and $\theta_e < 45°$, which are imposed due to limited detector acceptance. Cross section results are given in Figure 2, showing comparison to MC from several generators. While the limited phase space reduces the sensitivity to model differences, a slight preference toward the NEUT and GENIE models is observed.

5. $\bar{\nu}_\mu$CC0π0p at $\langle E_{\bar{\nu}} \rangle \sim 0.86$ GeV

The final result discussed was made using the commissioning set up for the WAGASCI detector, reporting the $\bar{\nu}_\mu$CC0π0p cross section at a mean energy of 0.86 GeV [10]. Signal is defined by searching for events with an antimuon-like track, with no pions or protons present. An additional sample is selected of both ν_μ and $\bar{\nu}_\mu$ interactions, to measure the total $\nu_\mu + \bar{\nu}_\mu$ cross section. Performing the selection in both the WAGASCI module and proton module enables cross section extraction on water and hydrocarbon, respectively, along with the ratio between them.

The measurement is made in the restricted phase space of $\theta_\mu < 30°$ and $p_\mu > 400$ MeV, and cross section results on water as a function of angle are given in Figure 3. These show mostly good agreement with the NEUT expectation, which is also observed for the hydrocarbon and $\frac{H_2O}{CH}$ measurements. This measurement is the first to be performed with the WAGASCI detector, and with the full setup now complete, further results are expected in the future.

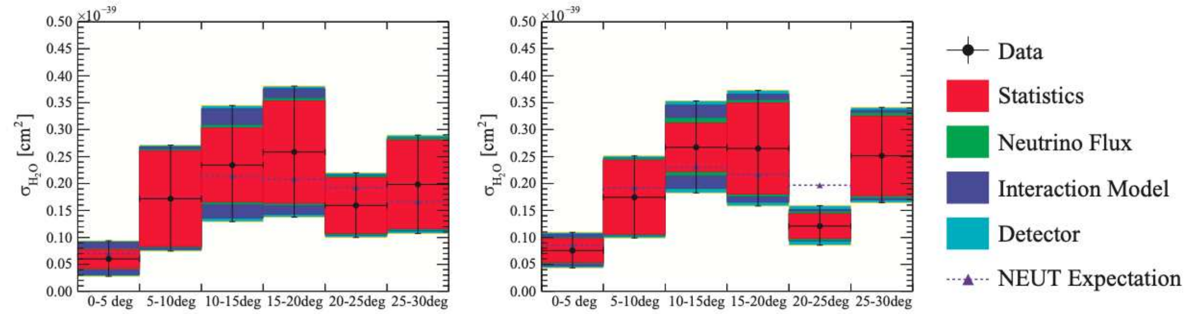

Figure 3: $\bar{\nu}_\mu$ and $\nu_\mu + \bar{\nu}_\mu$ cross section on water using WAGASCI commissioning setup, with comparison to NEUT expectation [10].

6. Summary

With multiple near detectors at differing off-axis angles, T2K is continuing to make a wide range of new cross section measurements, with many analyses currently in the works. The upcoming upgrade to the ND280 detector will further improve measurement capabilities, particularly in the high angle and low momentum phase space regions.

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